



Real-Time Ballistic Impact Deformation and Strain Measurements of Transparent TROGAMID Polyamides

by Alex J. Hsieh, Jian H. Yu, and John W. Song

ARL-TN-449

September 2011

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REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) September 2011		2. REPORT TYPE Final		3. DATES COVERED (From - To) September 2010–May 2011	
4. TITLE AND SUBTITLE Real-Time Ballistic Impact Deformation and Strain Measurements of Transparent TROGAMID Polyamides				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Alex J. Hsieh, Jian H. Yu, and John W. Song*				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Research Laboratory ATTN: RDRL-WMM-G Aberdeen Proving Ground, MD 21005-5069				8. PERFORMING ORGANIZATION REPORT NUMBER ARL-TN-449	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.					
13. SUPPLEMENTARY NOTES *U.S. Army Natick Research, Development, and Engineering Center, Natick, MA 01760					
14. ABSTRACT Dynamic deformation of two transparent TROGAMID polyamide materials upon ballistic impact is analyzed by utilizing a photogrammetric technique known as digital imaging correlation. The extent of out-of-plane deformation and shear deformation is greater in TROGAMID CX-7323 than in TROGAMID T-5000. These real-time, full-field deformation measurements at various impact velocities enable the differentiation and validation of mode of failure, which is not obtainable directly from the MIL-SPEC V ₅₀ measurements, between the two select polyamide materials. TROGAMID CX-7323 is more ductile than TROGAMID T-5000, despite their similar V ₅₀ values.					
15. SUBJECT TERMS transparent TROGAMID polyamides, digital imaging correlation, ballistic impact, out-of-plane deformation, shear deformation					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 18	19a. NAME OF RESPONSIBLE PERSON Alex J. Hsieh
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (Include area code) 410-306-0698

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Acknowledgments

Alex J. Hsieh and Jian H. Yu would like to acknowledge the partial funding support from Dr. John Song of the U.S. Army Natick Research, Development, and Engineering Center through MIPR0GDATN1055.

1. Introduction

Current state-of-the-art soldier eye protection systems, including military combat eye protective systems (MCEPS), are primarily fabricated from transparent polycarbonate (PC). PC is ductile and has very good impact performance, but it is susceptible to abrasion and chemical hazards. Additionally, PC is very notch-sensitive, and it undergoes a ductile-to-brittle transition noticeably in target plates greater than about 5–6 mm thick, particularly under extreme service (i.e., low temperature) conditions or after annealing. The geometry dependence of the mode of failure has been attributed to a change of stress state from plane stress to plane strain, thus suppressing yield deformation and favoring craze initiation and crack growth, subsequently leading to a catastrophic failure. The brittle deformation can be detrimental to the impact performance, as well as to critical operational requirements. This limitation on performance sustainability precludes the use of a PC monolith in the design of ballistic face shields for advanced combat helmets (ACHs) (shown in figure 1).



Figure 1. ACH helmet with face shield.

Transparent TROGAMID polyamides produced by Evonik Degussa High Performance Polymers are currently being evaluated as candidate face shield materials to replace PC for soldier eye protection. TROGAMID CX-7323 is reportedly composed of all aliphatic monomer units of dodecanedioic acid and 4,4'-methylenebis(cyclohexylamine) in comparison to an aromatic TROGAMID T-5000 (1). The glass transition temperature (T_g) of TROGAMID T-5000 is about 153 °C, while microcrystalline TROGAMID CX-7323 exhibits a lower T_g at about 140 °C (1). TROGAMID CX-7323 possesses significantly improved properties, including higher resistance to chemicals and stress cracking and a higher level of UV stability than PC. The property enhancement is partly attributed to microcrystallinity but is small enough not to scatter visible light (1). Upon heating above T_g , TROGAMID CX-7323 exhibits cold crystallization, followed by melting transition occurring at temperatures between 230 and 260 °C (2).

The mechanical properties also differ between the aliphatic TROGAMID CX-7323 and the aromatic TROGAMID T-5000. Table 1 lists the values of tensile modulus, yield stress, and tensile strain at yield, in which TROGAMID T-5000 is much stiffer than TROGAMID CX-7323 (1). Song and coworkers examined the ballistic impact performance of these two transparent polyamide materials, and their results showed that the ballistic limit (V_{50}) values with respect to the areal density appeared to be very similar (2). Both TROGAMID T-5000 and TROGAMID CX-7323 showed higher V_{50} values than PC and poly(methyl methacrylate) (PMMA) for target thickness in the vicinity for use in the ACH face shields application (figure 2) (2). TROGAMID T-5000 exhibited brittle failure with the presence of radial cracking upon penetration, while TROGAMID CX-7323 displayed ductile behavior upon ballistic impact against a 0.22-cal. fragment simulating projectile (FSP). Figures 3a and 3b compare the typical mode of failure upon impact seen in TROGAMID T-5000 and TROGAMID CX-7323, respectively (2).

Table 1. Mechanical properties of TROGAMID T-5000 and TROGAMID CX-7323 (1).

Materials	Tensile Modulus (MPa)	Yield Stress (MPa)	Yield Strain (mm/mm)
T-5000	2800	90	0.08
CX-7323	1400	60	0.08

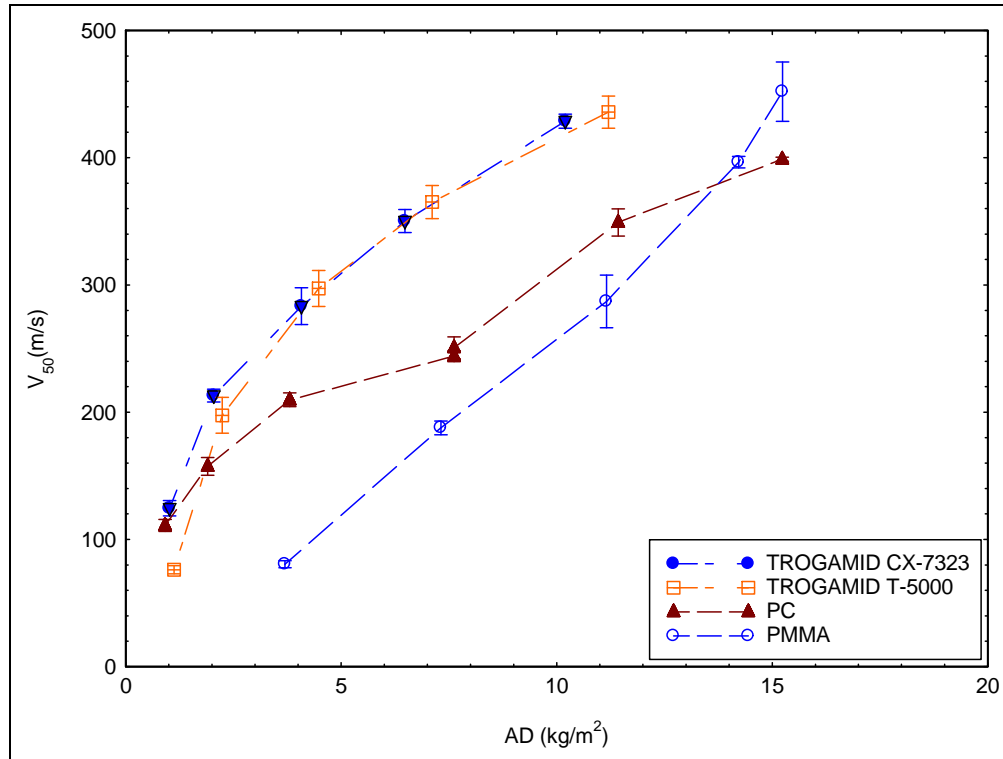


Figure 2. Ballistic limit (V_{50}) values as a function of areal density for TROGAMID T-5000, TROGAMID CX-7323, PC, and PMMA (2).

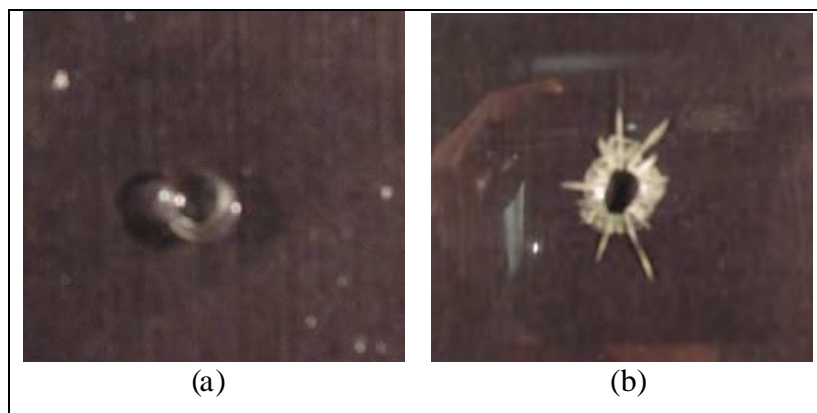


Figure 3. Typical mode of failure upon ballistic impact seen in (a) TROGAMID CX-7323 and (b) TROGAMID T-5000 (2).

In this work, digital imaging correlation technique is used to measure the real-time local deformation strain of TROGAMID polyamides upon ballistic impact. There has been a strong effort to develop a robust photogrammetric technique for real-time mechanical deformation analysis (3–7) in a broad range of materials characterization. Our objective is to utilize the real-time local strain deformation measurements for further correlation and validation of ballistic impact deformation response observed in these two transparent polyamide materials.

2. Experimental

2.1 Materials

Injection-molded, 1/4-in-thick plaques of transparent TROGAMID T-5000 and TROGAMID CX-7323 materials were obtained from Evonik Degussa High Performance Polymers for ballistic impact evaluation.

2.2 Ballistic Impact Measurements

Ballistic impacts measurements were carried out with a 17-gr (1.1-g), 0.22-cal. FSP. The gas gun was pressurized at different pressures with helium gas to propel the projectile to reach select impact velocities. The speed of the projectile was tracked with a Doppler radar (BR-3502, Infinition, Inc.). The polyamide target ($3.5 \times 3.5 \times 1/4$ in) was sandwiched in a target frame with a circular opening of 3 inches in diameter. The targets were spraypainted with a random pattern of white and black dots (figure 4). The dot size that appeared on the digital image was about 8 pixels in diameter.

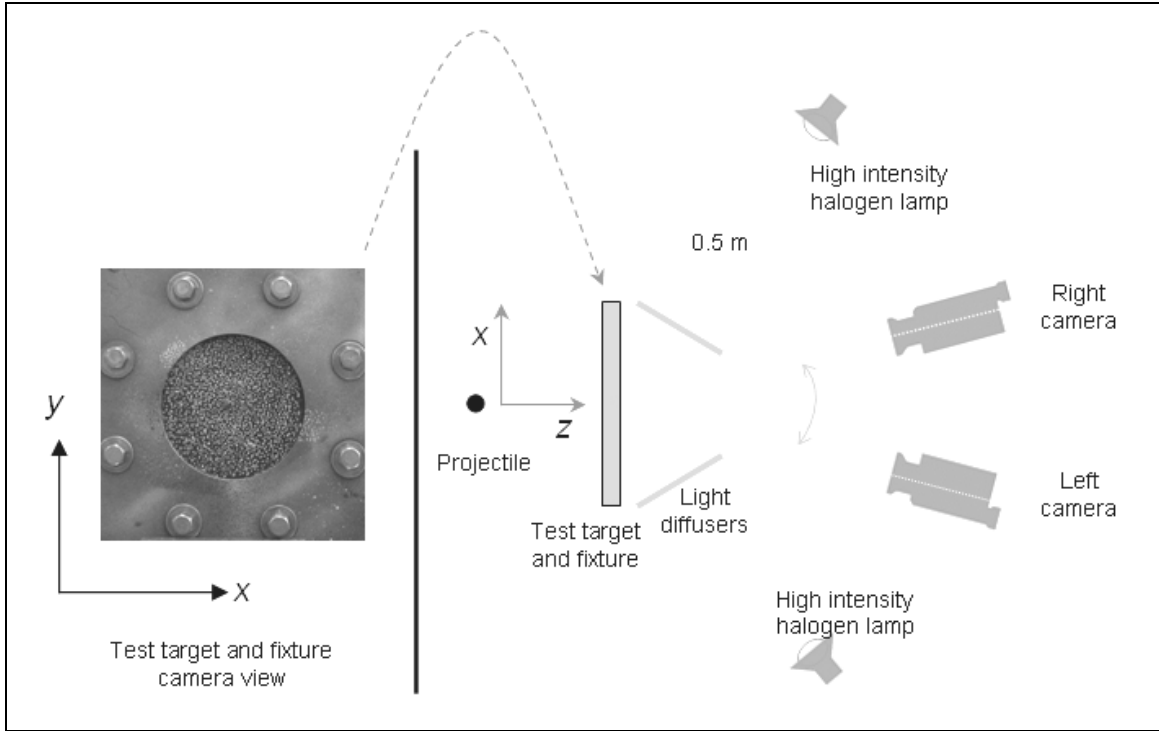


Figure 4. Impact experiment setup.

Two high-speed cameras (Photron SA1, Photron USA, Inc.) were used to generate stereo image pairs of the impact area. The two cameras were placed behind the target fixture. Details of the camera setup and images collection can be found in Yu et al. (7) and Yu and Dehmer (8). The stereo images were analyzed using the commercially available photogrammetric software program ARAMIS (GOM GmbH, Germany, distributed by Trilion Quality Systems in the U.S.). The cameras were calibrated with a series of standard dot images (8, 9). ARAMIS has a built-in algorithm for calculating the displacement. Details of the data analysis, including the determination of the displacement measurement sensitivity and the strain calculation sensitivity, can be found in Yu et al. (7) and Schmidt et al. (9). The ARAMIS software allows for calculation of displacement history in the transverse direction (ϵ_{xx} and ϵ_{yy}), as well as the corresponding shear component (ϵ_{xy}).

3. Results and Discussion

TROGAMID T-5000 and TROGAMID CX-7323 exhibited similar V_{50} values despite their difference in ballistic impact mode of failure. In order to better understand the role of microcrystallinity on the overall ballistic impact performance, it is important to first quantify and compare the dynamic deformation response between the two TROGAMID polyamide materials.

In this work, a digital imaging correlation technique that allows for real-time visualization of an impact deformation event is utilized to determine the local displacement evolution.

Full Field Deformation Elements

Figure 5 shows the time history of the deformed surfaces of the TROGAMID CX-7323 targets, which were impacted against a 0.22-cal. FSP at 167 and 350 m/s. The full-field, out-of-plane displacement profiles reveal the progress in the extent of dynamic deformation with increasing impact velocity. Initiation of failure, indicated by a discontinuity in the displacement history profiles, occurs as expected at shorter time upon impact at higher velocity. The ARAMIS software also allows for calculation of the shear strain deformation. Figure 6 displays the surface shear strain of TROGAMID CX-7323 at times after impact.

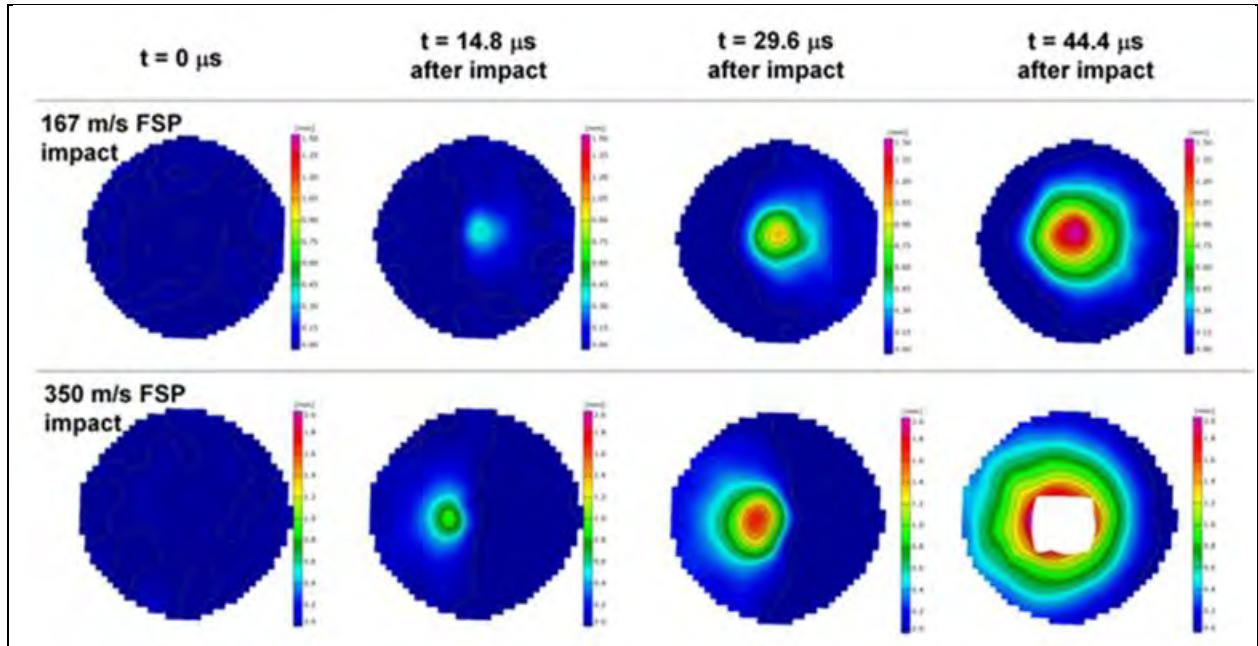


Figure 5. Plots of out-of-plane deformation history measured by impact of TROGAMID CX-7323 against a 0.22-cal. FSP at velocities of 167 and 350 m/s (the white spot is indicative of a discontinuity due to fracture).

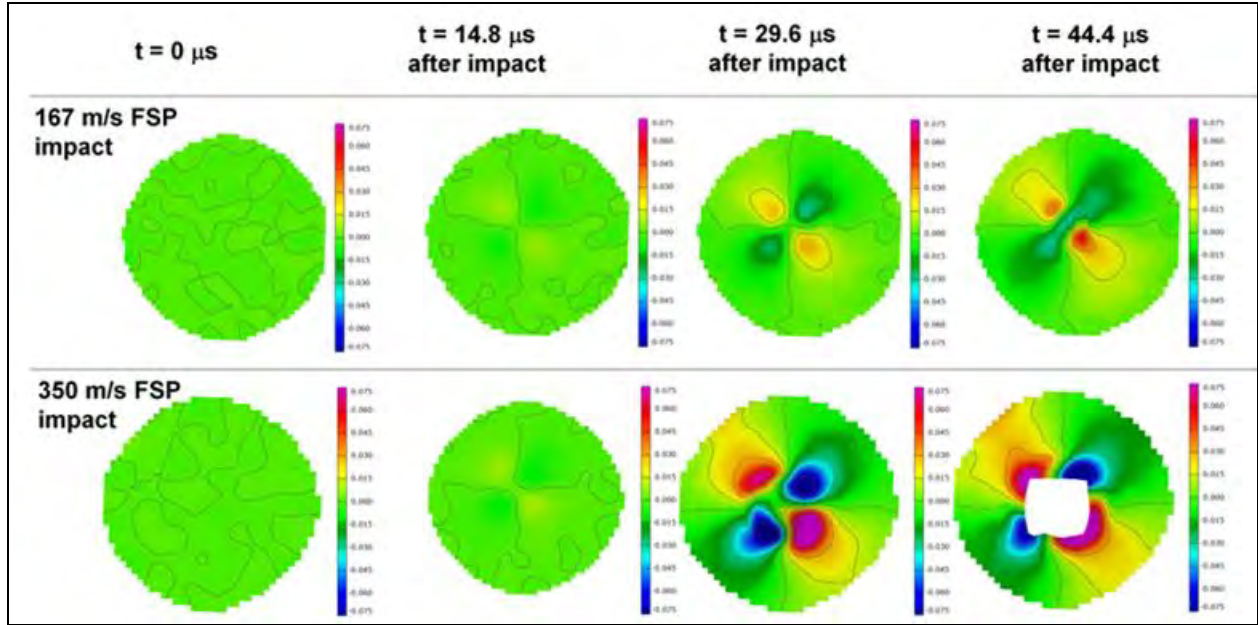


Figure 6. Plots of the surface shear strain, ϵ_{xy} , of TROGAMID CX-7323 against a 0.22-cal. FSP at velocities of 167 and 350 m/s (the white spot is indicative of a discontinuity due to the penetration of the FSP).

The extent of out-of-plane displacement in TROGAMID CX-7323 is more significant in comparison with the corresponding time history plot shown in figure 7 for TROGAMID T-5000. Similarly, TROGAMID CX-7323 exhibits greater shear deformation in comparison with TROGAMID T-5000, as shown in figure 8.

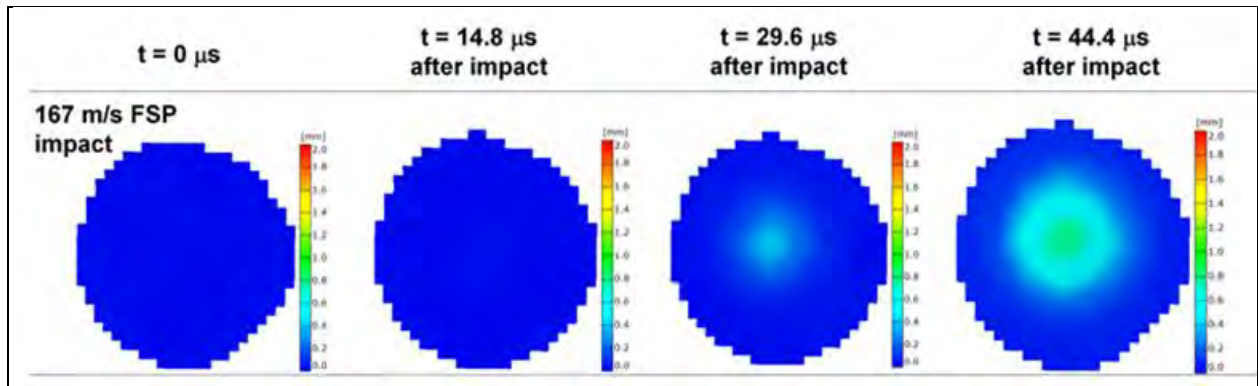


Figure 7. Plots of out-of-plane deformation history measured by impact of TROGAMID T-5000 against a 0.22-cal. FSP at a velocity of 167 m/s.

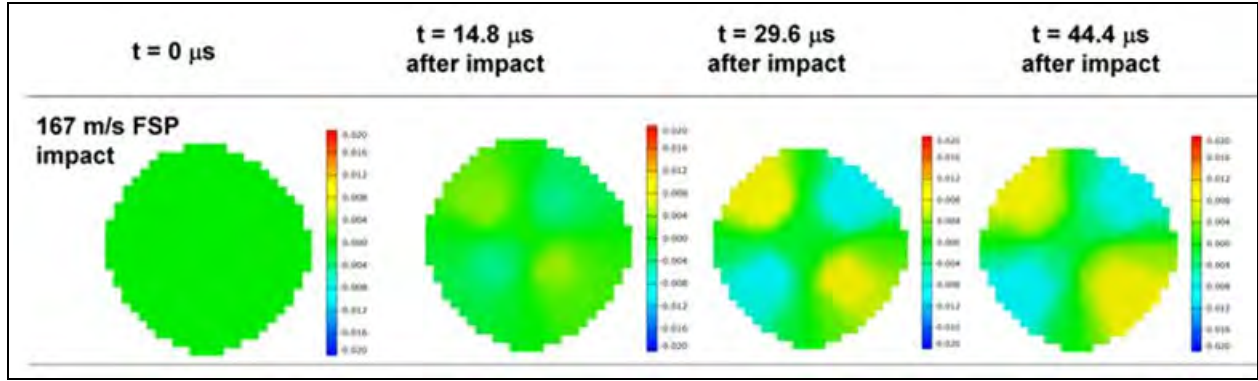


Figure 8. Plots of the surface shear strain, ϵ_{xy} , of TROGAMID T-5000 against a 0.22-cal. FSP at a velocity of 167 m/s.

Figure 9 compares the surface displacement history data obtained for TROGAMID CX-7323 and TROGAMID T-5000 at impact velocity of about 167 m/s. Both materials exhibit similar deformation until $\sim 30 \mu\text{s}$ after impact, and thereafter TROGAMID CX-7323 continues to deform, suggesting TROGAMID CX-7323 is more flexible than TROGAMID T-5000. This is consistent to the quasi-static mechanical properties shown in table 1. As impact velocity further increases to 268 m/s, the initial rate of deformation appears to be similar, while the maximal surface displacement increases in both TROGAMID CX-7323 and TROGAMID T-5000 (figure 10). TROGAMID CX-7323 remains intact; however, TROGAMID T-5000 appears close to the failure limit at about $40 \mu\text{s}$ after impact. These observations clearly validate that TROGAMID CX-7323 exhibits noticeably ductile deformation in comparison to TROGAMID T-5000, despite their similar V_{50} values.

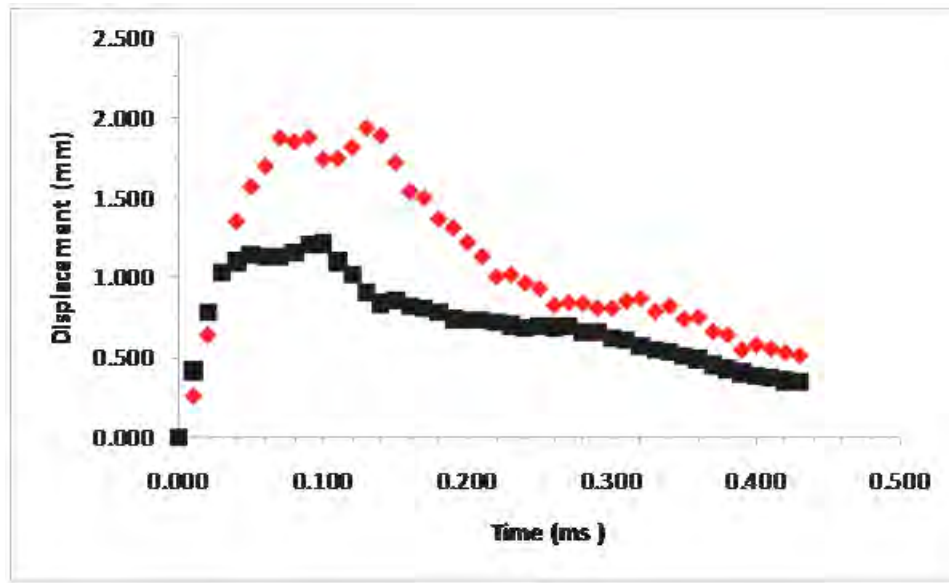


Figure 9. Plots of surface displacement history obtained at impact velocity of 167 m/s for TROGAMID CX-7323 (red) and TROGAMID T-5000 (black).

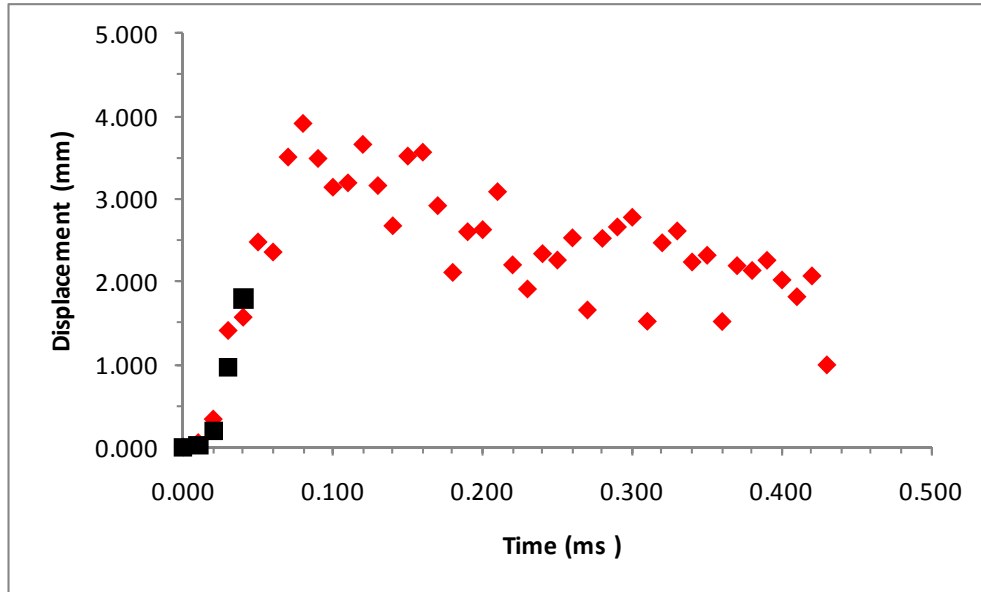


Figure 10. Plots of surface displacement history obtained at impact velocity of 268 m/s for TROGAMID CX-7323 (red) and TROGAMID T-5000 (black).

4. Summary

Ballistic impact deformation of transparent TROGAMID polyamide materials was investigated. A novel digital imaging correlation technique capable of providing real-time, full-field deformation measurements is a viable approach for use to differentiate dynamic impact deformation between an aliphatic TROGAMID CX-7323 and an aromatic TROGAMID T-5000. These observations, which are not obtainable directly from the MIL-SPEC V_{50} measurements, will enable the materials design and integration of transparent face shields for the next generation of ACH helmets.

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